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Centennial of Gibbs' Thermodynamics—Concluding Remarks

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The President's reference to the 18 years that have elapsed since I held the position he now occupies is one of two recent instances that have reminded me of the rapid passage of time. The other occurred a few days ago when, in preparation for this symposium, I looked into the volumes of Gibbs' collected works that I first studied some 45 years ago. Although I had remembered vividly the pleasure that came from following the closely knit arguments and ingenious graphical demonstrations that led him from two very simply stated but pregnant general principles to elucidate phenomena and laws covering a vast area of physical chemistry, I found with some dismay that much of the content seemed unfamiliar, forgotten over years of preoccupation with other matters. Only handwritten marginal notes assured me that once I had studied these papers assiduously. The papers tonight brought alive again the realization that those articles published—mostly in the Transactions of the Connecticut Academy approximately a century ago—are still a rich mine of scientific gold.

Let me base these concluding remarks on a passage from a memorial biography[1] written in 1903 by H. A. Bumstead, a student and colleague of Gibbs, and later Professor of Physics and Director for many years of the Sloane Physics Laboratory at Yale:

> "Although he disregarded many of the shibboleths of the mathematical rigorists, his logical processes were really of the most severe type; in power of deduction, of generalization, in insight into hidden relations, in critical acumen, utter lack of prejudice, and in the philosophical breadth of his view of the object and aim of physics, he has had few superiors in the history of the sciences; and no student could come in contact with this serene and impartial mind without feeling profoundly its influence in all his future studies of nature."

Through the exercise of these *logical processes*, Gibbs left a legacy of elegant instruments of thought such as the concept of the chemical potential (often very loosely called the "Free Energy" or "Partial Free Energy") together with

[1] American Journal of Science, Series 4, Vol. XV, September 1903. Reprinted in "The Collected Works of J. Willard Gibbs, Vol. I, Longmans, Green & Co., New York, 1928.

equations and diagrams using this concept. Dr. Rumble has shown how these methods, combined with a knowledge of the components present in a geochemical system, can enable the ingenious investigator to thread his way through the maze of complicated reactions taking place in the formation of metamorphic rocks and deduce the conditions under which they were formed, thereby strengthening our knowledge of the thermal history of the earth's crust. Dr. Mountain has shown us that the graphical expressions logically derived by Gibbs to describe, among other things, the thermodynamics of critical phenomena have relevance not only to the classical cases but also to "phase" transitions which are some of the most exciting phenomena in modern solid state physics.

Gibbs' *insight into hidden relations* implicit in simple, empirically established general principles is a feature of "On the Equilibrium of Heterogeneous Substances" that strikes the attention of any reader. In following his logical arguments relentlessly to take into account all imaginable variables that might influence a system, such as *gravity, capillarity, and electromotive force*, Gibbs formulated relationships that over the years have assumed more and more general significance. Dr. Morowitz has laid before us many examples illustrating clearly the direct and indirect consequences in the fundamental exploration of biological systems of "hidden relations" uncovered by Gibbs.

Taken together, the discussions we have heard tonight amply endorse Bumstead's assessment of the surpassing *philosophical breadth of his (Gibbs') view of the object and aim of physics.*

Although this symposium is primarily concerned with the thermodynamics of Gibbs, I can not refrain from a further remark inspired by a statement made by Dr. Morowitz concerning Gibbs' studies of statistical mechanics to the effect that the mathematical statistical structure Gibbs developed now transcends in importance the mechanics that have been incorporated into it.

The following extract[2] from the preface to "Elementary Principles in Statistical Mechanics" is illuminating:

> " . . . Even if we confine our attention to the phenomena distinctively thermodynamic, we do not escape difficulties in as simple a matter as the number of degrees of freedom of a diatomic gas. It is well known that while theory would assign to the gas six degrees of freedom per molecule, in our experiments on specific heat, we cannot account for more than five. Certainly, one is building on an insecure foundation, who rests his work on hypotheses concerning the constitution of matter.
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> "Difficulties of this kind have deterred the author from attempting to explain the mysteries of nature, and have forced him to be contented with the more modest aim of deducing some of the more obvious propositions relating to the statistical branch of mechanics. Here, there can be no mistake in regard to the agreement of the hypotheses with the facts of nature, for nothing is assumed in that respect. The only error into which one can fall, is the want of agreement between the premises and the conclusions, and this, with care, one may hope, in the main, to avoid."

The choice and definition of a subject to which he is to devote his time and effort for an indefinite period is the most important decision a scientific investigator makes. The problem must be significant, material for its solution must be at least foreseeable, and the solution must be within, indeed call for, the highest intellectual powers of the investigator. The ability of a person to assess these conditions and choose appropriate problems proclaims the genius of the investigator and separates the first class from the nth class scientist.

These criteria are compatible with Gibbs' rank as a first class natural philosopher, although, if confronted with his proposal, it is not so certain that "blue ribbon" panels today would have supported his effort.

Tonight's symposium brings out clearly that the thinking of Gibbs has had a lasting influence on the theoretical and experimental development of all areas of modern science.

Let me now call attention to an area of human activity where the example of

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[2] "The Collected Works of J. Willard Gibbs, Vol. II, Longmans, Green & Co., New York, 1928, p. x (preface).

Gibbs' life and work has considerable relevance but which now goes on as if he and other thinkers had not existed. You will recall that the series of papers "On the Equilibrium of Heterogeneous Substances"[3] began with the following words:

" '*Die Energie der Welt ist constant.*
Die Entropie der Welt strebt einem Maximum zu.'

—*Clausius*

The comprehension of the laws which govern any material system is greatly facilitated by considering the energy and entropy of the system in the various states of which it is capable."

On the basis of these empirical principles Gibbs gives as the criterion for a system (isolated) to be in equilibrium, any change in the state of the system must be such that $(\delta S)_E \leqq 0$, where S is the entropy and E the energy of the system. Without introduction of energy from without the system in equilibrium has no potential for yielding useful work and is dead. In moving towards this state of equilibrium, the system undergoes a number of spontaneous changes in which the useful work given out under specific conditions may be expressed as $W = \Delta E - T\Delta S$. If these changes take place *reversibly*—i.e., they are held in control by a mechanism that constrains them to take place under equilibrium conditions, slowly enough, the work that can be obtained approaches its maximum value.

If, on the other hand, these changes are uncontrolled, highly irreversible, the useful work obtained for a given energy change is much less than the maximum obtainable, indeed sometimes close to 0, the energy being all absorbed by $T\Delta S$, the system rushes rapidly and wastefully to the equilibrium state where the entropy takes on its maximum value. For example, if we burn hydrogen and oxygen in a flame no useful work results, with an intermediate device such as a steam engine we may obtain some useful work at the expense of the entropy increase, with a fuel cell we may control the speed of the hydrogen oxygen reaction by sensing and adjusting the electromotive force of the cell in a way that brings the useful work yielded as close to the maximum as we wish. The human body is well supplied with control mechanisms which sense departure from equilibrium conditions and control the processes taking place to use most economically the energy intrinsic in the food we eat and the air we breathe.

Today, we are in the midst of a so-called "energy crisis." The word "energy" is used by the propagandists of all kinds to lend an aura of scientific dignity in making capital out of a situation in which the demand for certain non-renewable (or rather difficultly renewable) resources exceed the supply, fuel now and metals soon being the chief items of concern. If one has to use a word, well defined in science but not well understood elsewhere, it might be better to describe the current situation as an "entropy crisis". This term would at least cover three important current problems and emphasize the close relationship between them. For the current fuel or "free energy" crisis that commands so much public attention—written and spoken words today—the pollution or waste problem that held the center of the stage yesterday, and the materials problem which will arouse as much concern tomorrow; all arise from a common source, uncontrolled dispersal of resources—runaway increase of entropy, to state the matter succinctly if loosely.

I have spoken of the role of control systems in regulating the processes whereby nature permits us to extract from the resources[4] assembled over millions of years "useful work" and its

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[3]Transactions of the Connecticut Academy, III, pp. 108–248, Oct. 1875–May, 1876, and pp. 343–524, May 1877–July 1878.

[4]Looking at "non renewable" resources such as fossil fuels, metallic ore concentrations, we may consider the earth to be an isolated system. However, as regards "renewable" resources such as water power, farm and forest products, the earth is not an isolated system; the energy received from the sun continually reducing the entropy, increasing the potential of part of the system to yield useful work.

social equivalent, commodities, services, and even luxuries.[5] Through intellects like that of Gibbs, man has learned that there are fundamental limits to these processes and, within these limits, how to realize the maximum benefits from them.

The resources of the earth are vast but not unlimited, and it is high time that this knowledge was used to greater social effect, but to do so may require very fundamental changes in our thoughts and communications. An essential feature of the control of any process or machine is "negative feed back control." A sensor gives *timely* and *accurate* information concerning the present magnitude and trend of the output of the process or machine; in a comparator this information is compared with what the magnitudes and trends should be to preserve stable and efficient operations, and differences are converted into information signals sent to change the input of the machine to *oppose* undesirable trends in its operation. Thus stability is maintained. If because information concerning the output is *untimely, inaccurate*, or the system is deliberately so designed, increase in the output may result in *increase* in the input, and the control system reinforces rather than opposes trends in the system's operation. This is known as "positive feed back" and results in exponential growth of the speed of the output of the process or machine. Explosions, be they in bombs, population, pollution or knowledge, all involve "positive feed backs." Such processes are irreversible, large amounts of energy being required to restore the system to its original state.

Social systems may be regarded as complex, dynamic and sensitive machines, designed to promote survival in a hostile environment of the system itself and of its individual components. Their successful operation depends on the sophistication and reliability of their control systems to conduct operations in accordance with the laws of nature, in particular the laws of thermodynamics. In democratic societies the input of the social machine is basically through the motivation, thought and action of the individual, the output is group behavior, concerted effort to optimize the creation of intellectual and material products needed to support the life and welfare of the system. The control system in a modern society is very complex. There are many sensors detecting and predicting the outputs and trends of the system—public servants, writers, philosophers, and religious leaders, to give some examples. The "information" generated by these sensors may or may not be timely and accurate, and, when processed through the comparator furnished with the corporate memory of history, yields control signals of varying and often unknown quality, often being tinged with the human tendency to dramatic exaggeration. The channels communicating these signals to the input also introduce the noise of untimeliness, uncertainty and error. Thus the signals, arriving at the input of the machine are very noisy, the negative feed backs so necessary to stability often being submerged by stronger messages causing positive feed backs and introducing hysteria or crisis psychology into the motivation of the individual.

This is not at all an ideal state of affairs and I fear that the scientific segment of society is by no means free from non-ideal observations, formulations, communications and motivations. However, the experience of mankind gives no hope of a system-wide improvement—we must turn to the individual. A key to the individual response is given in the last phrases of the above quotation from Gibbs' biographer:

> " . . . and no student could come in contact with this serene and impartial mind without feeling profoundly its influence in all his future studies of nature."

We might conjecture that the serenity and impartiality of this mind came from its will and ability to discern in strident

[5] The word "wealth" as used by classical economists describes the social equivalent of "useful work."

and noisy communications pouring in from all sides the "still small voice" of truth, and its determination to follow rigorously courses of action motivated by this truth and this truth alone. After a century this serene and impartial mind still shines through the great scientific works of Willard Gibbs, giving to the student, overwhelmed by the inconsistencies, the confusion and violence of the world of today, determination to refine the gold of truth from the dross of falsehood and error, and courage to follow this truth relentlessly.
